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The impact of emissions and climate change on future ozone concentrations in the USA

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Abstract
The potential impacts of climate change and future anthropogenic emissions on ozone levels in the USA are examined by linking global climate models to regional meteorological and air quality models during 3-year summer periods over the nine climate regions of the continental United States for three cases: (1) using 2016 meteorology and emissions (CTRL), (2) using 2050 meteorology and 2016 emissions (CASE1), and (3) using 2050 meteorology and 2050 emissions (CASE2). As climate change alone is expected to worsen ozone pollution and emission reductions are expected to reduce ozone concentrations, in this paper, the non-linear response of future ozone levels to both meteorological conditions and emissions was studied. The results show the well-known positive ozone correlation with surface temperature and negative ozone correlation with humidity in all regions. Climate change alone will increase future MDA8 ozone in the USA by 3.6 ppb. With climate change and policy intervention based on RCP 8.5, ozone levels will decrease 7.2 ppb on average for all climate regions in the USA. Furthermore, while climate change alone will double the number of stations violating the current National Ambient Air Quality Standard (NAAQS) for ozone in 2050, when policies are in effect, this number was reduced to 21 stations. The number of high-ozone days will also increase in climate change only case in all regions with an average of 5.7 extra high-ozone days which confirms previous studies. The results show that even with high-ozone precursor reductions, the ozone levels will still violate the current national ozone standard. Therefore, in order to meet the current ozone standard by 2050, more stringent climate and air pollution control policies for most regions in the USA are needed.

Keywords Air pollution · Ozone · Air quality modeling · Climate change · Emissions

Introduction

Future projections of air quality should account for changes in both climate and emissions due to their combined impacts on air quality. For ground-level ozone pollution, the most important factors are precursor emissions (NO_x and VOC) and favorable meteorological conditions (Jacob and Winner 2009; Nolte et al. 2008). Although the emissions of ozone precursors in the USA have declined significantly in the past decades and led to improvements in air quality and human health (United States Environmental Protection Agency 2012), climate change itself will worsen ozone pollution by increasing the frequency of high-ozone days by mid-century (Archer et al. 2019) in the absence of emission changes.

As ozone pollution is highly sensitive to meteorology, climate change has the potential to affect air quality by modifying temperatures, wind speeds, mixing heights, humidity, clouds, and precipitation, which all affect pollutant formation and removal rates (Jacob and Winner 2009; Westervelt et al. 2016; Fiore et al. 2015). According to a recent study by Archer et al., it will take only two years to have an additional high-ozone day due to climate change by the mid-century, while historically it took five years to have an additional high-ozone day (Archer et al. 2019). This is because of an increase in the frequency of synoptic conditions favorable to high ozone, an increase in daily mean temperature, and a decrease in the number of days with precipitation. Furthermore, studies using global and regional models found that climate change alone will increase summertime surface ozone in polluted regions by 1–10 ppb over the coming decades, with the largest effects in urban areas and during pollution episodes (Doherty et al.

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2013; Gao et al. 2013; Jacob and Winner 2009; Penrod et al. 2014; Nolte et al. 2018; Stowell et al. 2017; Kim et al. 2015). This climate penalty means that stronger emission controls will be needed to meet a given air quality standard.

Moreover, the air quality in the future will be affected by any change in the emissions of primary air pollutants and precursors of secondary pollutants. Although as a result of regulatory actions, such as the Cross-State Air Pollution Rule (CSAPR) and the Tier 2 and Tier 3 emission standards for motor vehicles, anthropogenic emissions in general are projected to continue their downward trend (United States Environmental Protection Agency (USEPA) 2015; Iny et al. 2015), and future anthropogenic emissions of ozone precursors are uncertain. A number of future emission reduction scenarios have been developed based on socio-economic projections, which could be interpreted as a range of possible changes of future emissions (Riahi et al. 2011; Kim et al. 2015; Gidden et al. 2019). Although these projections show a huge decrease in emissions of ozone precursors by mid-century, the effect of such emission reductions on ozone levels is not clear. For example, relatively small ozone precursor emission reductions (10% reduction for NO_x and VOC) over the US Mid-Atlantic region would help states inside and even outside the region to reach attainment of 2015 National Ambient Air Quality Standards (NAAQS) for ozone because of ozone transport (Moghani et al. 2018). On the other hand, a few previous studies on the effect of climate change and/or emissions on the future ozone concentrations in the USA have shown that future ozone concentrations will increase at times even though there are no emission reductions in effect (Nolte et al. 2018; Gonzalez-Abraham et al. 2015). However, when climate and air pollution control policies are in effect, depending on the adopted scenario and the geographical location, the ozone levels could be lower or higher (Gao et al. 2013; Gonzalez-Abraham et al. 2015; Stowell et al. 2017; Zhang et al. 2016). In 2018, Nolte et al. (2018) studied the impact of climate change on 2030 ozone and PM levels in the USA with no policy intervention using CMAQ under different representative concentration pathways (RCPs). While the anthropogenic emissions and boundary conditions were unchanged between the historical and future periods to isolate the meteorological effects of climate change from non-meteorological factors, results indicated increases in seasonal mean maximum daily 8-h average (MDA8) O3 during summer in the Northern Rockies, Upper Midwest, Ohio Valley, and Northeast regions under all scenarios. The increase was largest under RCP 8.5, exceeding 4 ppb in parts of the Northern Rockies and Upper Midwest regions. In another study by Collet et al. (2017) on the effects of only emissions on ozone and PM in 2030 in the USA, it showed that the number of stations exceeding the NAAQS of 70 ppb will be limited and that a 14-ppb improvement is expected from 2011 to 2030 on average. Therefore, it is important to consider both climate change and emission reductions in a single study to have a better estimate of the future ozone levels.

Due to the coarse resolution of global climate models (GCMs), there is a lack of useful local air quality information for policy makers. Here we adopt the dynamical downscaling technique of Gao et al. (2013) to link global and regional models, which uses relatively coarse resolution initial and boundary conditions from a GCM as drivers for a regional model, which results in high-resolution simulations. This technique is widely used to investigate the effects of climate change on air quality over the USA (Gao et al. 2013; Trail et al. 2013; Penrod et al. 2014; Gonzalez-Abraham et al. 2015). In order to take into account the effect of emissions on future ozone concentrations, the most recent 2016 EPA National Emission Inventory (NEI) is projected to the future using the current and future emissions mass ratio based on RCP 8.5. RCP 8.5 combines assumptions about high population growth and relatively slow income growth, with modest rates of technological advances and energy intensity improvements, leading to high energy demand and greenhouse gas (GHG) emissions in the absence of climate change policies in the long term. RCP 8.5 is a so-called baseline scenario because the GHG emissions and concentrations in this scenario increase considerably over time, leading to a radiative forcing of 8.5 W/m^2 at the end of the century (Riahi et al. 2011). In this method, we assume that the future spatial and temporal distributions of emissions are the same as in 2016.

The objective of this study is to estimate future ozone levels due to the combined effects of climate change and anthropogenic emissions when less stringent air pollution control and no climate policy (RCP 8.5) is in effect. In this study, we used the most updated versions of the air quality and meteorological models available, Comprehensive Air Quality Model with Extensions (CAMx) version 6.5 and the Weather Research and Forecasting model (WRF) version 4.0. As all previous studies used the EPA's 2011 or earlier NEI, and due to the non-linear response of ozone to emissions (Cohan et al. 2005), we used the most updated EPA NEI for 2016, which was released in 2019. The future emissions were scaled by applying the emission trends obtained from the RCP 8.5 using the same temporal and spatial resolutions as the 2016 emissions; further details can be found in Section 1. Although we studied ozone over the continental United States domain, we benefited from a relatively fine resolution (12 km). We used GEOS-Chem model to create the 2016 initial and boundary conditions for the control case (CTRL) over the USA and it will remain the same for all the future cases.

Model setup

In this study, we use a regional photo-chemical air quality model (CAMx), a regional meteorological model (WRF), a global climate model (Community Earth System Model, CESM), and a global atmospheric chemistry model (GEOS-Chem) to investigate ground-level ozone changes due to climate and anthropogenic emission changes in the USA. Details of the four models are provided in the next sections. The control case (CTRL) with 2016 meteorology and 2016 emissions is compared with two future cases. The first future case (CASE1) with 2050 meteorology and 2016 emissions represents the changes in ozone due to meteorological effects of climate change only. The second future case (CASE2) with 2050 meteorology and 2050 emissions represents the changes in ozone due to the combined effects of climate change and emission reductions (Table 1). To enhance statistical significance while keeping computational requirements reasonable and due to the temperature dependence of the ozone generation rate (Belan et al. 2018), we performed the control and future case runs for three consecutive summers. The control case spans over three summers using 2015–2017 meteorology with the same 2016 emissions for all three years. The future cases span over three summers using 2049–2051 future meteorology.

In all RCP scenarios, it is assumed that, as income levels grow over time, the air pollution controls will be more stringent, which means overall emission reductions when compared with today. However, emission reductions vary across RCP scenarios. The scenarios with strict climate policy (RCP 2.6) have the lowest emissions while the RCP 8.5, which is without climate policy, has the highest emissions (Van Vuuren et al. 2011). The RCP 8.5 scenario was chosen in this study to show how ozone concentrations will change when no climate policy is in effect, meaning that GHG emissions (e.g., methane) will continue to increase by 2050. On the other hand, policy- and technology-driven emission reductions are still in effect.

Studies (Nazarenko et al. 2015; United States Environmental Protection Agency (USEPA) 2016) have shown that the average temperature increased by 1.13 °C between 2000 to 2015 in the USA, while the projected temperatures under RCP 2.6, RCP 4.5, and RCP 6.0 over the same period showed an increase of 0.75 °C, 1.11 °C, and 1.03 °C respectively. This temperature increase is 1.56 °C for RCP 8.5. The RCP 8.5 scenario was therefore chosen in this study because the US temperatures have already risen beyond the projections of the RCP 2.6 scenario and are already aligned with (or exceeding) the warming projected by the RCP 4.5 and RCP 6.0 scenarios. Thus, we will provide non-optimistic predictions of ozone concentrations in the USA when less stringent air pollution control and no climate policies are in effect, which will help us find out whether the ozone levels in the USA will comply with the current (70 ppb) or possible future more stringent ozone standards (e.g., 60 ppb).

RCP 8.5 is a high-GHG emission pathway corresponding to the stabilization of radiative forcing at 8.5 w/m^2 in the year 2100, and it assumes high population growth rate, lower income, and lower technology development rate in developing countries (Riahi et al. 2011). The emission trends in the RCPs are mainly controlled by the driving forces (population, income, energy use, etc.), climate policy, and air pollution control policy (Van Vuuren et al. 2011). In terms of climate policy, RCP 4.5 has more stringent GHG emissions controls, while RCP 8.5 assumes no climate policy, even though both scenarios are projected to increase the use of renewable resources. Under the RCPs, ozone precursors including carbon monoxide (CO), nitrogen oxides (NO_x), and non-methane volatile organic compounds (NMVOC) are projected to decrease in the USA. However, GHG emission increases, particularly methane, under RCP 8.5 will negatively affect ozone air quality. As a result, the projected ozone levels in 2049–2051 in this study reflect the impact of both climate change and (modest) emission controls on ozone precursors. The control case, which is centered around 2016, was selected because it is the year of the most recent EPA's NEI. The future cases, which center around 2050, were selected to represent mid-century conditions. The modeling domain covers the continental United States as shown in Fig. 1 with a 12-km horizontal resolution and 34 vertical layers.

Table 1 Details of the CAMx simulations

Case name	Meteorology	Emissions
CTRL (control)	2015–2017	2016
CASE1 (climate only)	2049–2051	2016
CASE2 (climate and emissions)	2049–2051	2050

Global climate model

The climate model used here is the National Center for Atmospheric Research's (NCAR) Community Earth System Model (CESM1), which was part of phase 5 of the Coupled Model Intercomparison Experiment (CMIP5) in support of the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5). The dataset is the global bias-corrected climate model output data from version 1 of CESM (Monaghan et al. 2014). The dataset contains all the variables needed for the initial and boundary conditions for the WRF simulations. The data are interpolated to 26 pressure levels and are provided in six-hour intervals. The variables were bias-corrected using the European Centre for Medium-Range Weather Forecasts (ECMWF) Interim Reanalysis (ERA-Interim) fields for 1981–2005, following

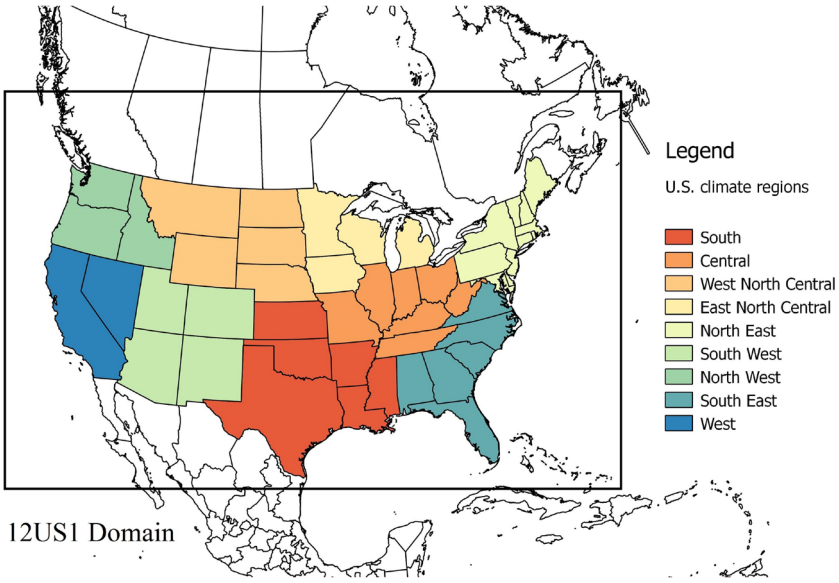

Fig. 1 The CAMx modeling domain used in this study, covering the continental United States, with the nine climatically consistent regions

the method in Bruyere et al. (2015). We used RCP 8.5 files spanning 2006–2100 to run the CTRL (2015–2017) and CASE1 and CASE2 (2049–2051) meteorological runs.

Regional climate model

The meteorological model is the WRF model version 4.0 (Skamarock and Klemp 2008). Selected physics options, following the EPA 2011 meteorological model performance technical support document (United States Environmental Protection Agency (US EPA) 2014), include Pleim-Xiu land surface model, Asymmetric Convective Model version 2 (ACM2) planetary boundary layer scheme, Kain-Fritsch cumulus parameterization utilizing the moisture-advection trigger, Morrison double moment microphysics, and RRTMG longwave and shortwave radiation schemes (Gilliam and Pleim 2010). WRF was initialized at 00:00 UTC 1 May for all years in the historical and future runs, so that each regional climate simulation included a 1-month spin-up period. We used the WRFCAMx meteorological data processing program to generate meteorological inputs for the CAMx model (Ramboll Environ 2017). The meteorological domain consisted of a 12-km grid (472×312 grid points) encompassing the continental United States. The vertical grid structure consisted of 34 layers with the highest number of levels in the lower heights. The initial and boundary conditions for the WRF model were obtained from version 1 of the CESM model for RCP 8.5 in both three-year periods of CTRL and of CASE1 and CASE2.

Chemical transport model

The air quality model is the most recent CAMx model (v6.50), which was used to simulate the control and future ozone concentrations in the USA with the carbon bond 6 (CB6) gas-phase chemical mechanism (Yarwood et al. 2010). A uniform grid of 12 km by 12 km horizontal cells (459×299) with 34 vertical layers was employed in the CAMx simulations over the USA. The depth of each vertical layer is different and the near-surface layers have smaller depth (e.g., the lowest vertical layer depth is ~23 m) to get more detailed ozone concentrations near the ground level. The chemical lateral boundary conditions and initial conditions were derived from an independent simulation of the year 2016 by GEOS-Chem 12.2.1 global chemical transport model (Henderson et al. 2014) for all of the control and the future case simulations. We did not consider the effects of global changes on the US ozone and the future changes on biogenic emissions and boundary conditions and such considerations can be found in other studies (e.g., Gonzalez-Abraham et al 2015).

Emission projections

We used the most updated version of the US EPA's 2016 NEI (beta version), which was released in March 2019, and projected the emissions based on RCP 8.5 for the future cases (Riahi et al. 2007). In the RCP 8.5 scenario, the mean emissions globally are projected to decrease (Meinshausen et al. 2011) and the NO_x and VOC emissions in the USA face a large decrease, while the methane emissions are projected to increase by 2050 (Table 2). In the USA, this decrease is more localized in the industrial and high-population eastern states and in the Western United States it occurs more in urban areas. As the RCP 8.5 reports emissions every 10 years, for each pollutant, we projected the 2010 US emissions to 2016 according to the 2010–2020 trend and then projected this value to the RCP 8.5 2050

Table 2 Anthropogenic emissions for the CTRL and future case (CASE2) in million tons (Mt) based on RCP 8.5

	CTRL (Mt)	RCP 8.5 (Mt)	Change (%)
NO_x	11.3	6.2	−45.2
NMVOC	16.4	8.3	−49.5
CH4	28.7	40.2	40.0
CO	61.8	18.7	−69.8
PM10	18.1	10.4	−42.4
PM2.5	5.3	2.7	−49.1
SO2	2.9	0.8	−74.8
NH3	3.6	4.7	31.6

US emissions for the same pollutant to obtain the growth factor. We applied this positive or negative growth factor to the anthropogenic emissions of each pollutant in the 2016 NEI to create the 2050 emissions. By the end of 2050, most anthropogenic emissions in the USA will decrease under RCP 8.5 scenario. For example, the NO_x, NMVOC, CO, and SO2 anthropogenic emissions will decrease by 45.2%, 49.5%, 69.8%, and 74.8% respectively, while the emissions of NH3 and CH4 will experience an increase of 31.6% and 40%. For all VOC species in the 2016 NEI, we applied the same growth factor. Although the biogenic emissions are expected to increase in future due to the increases in temperature (Gao et al. 2013), for the future projection runs, the biogenic emissions are held constant. It is expected that because of the temperature dependency of the biogenic VOC emissions, mainly in the South East region, the biogenic VOC emissions will be higher in the future (Jacob and Winner 2009) and this could affect the O3 levels in that region. We note that this is just one method to project current emissions to the future and it does not account the considerations of future changes in land use, population density or migration patterns, coal plants shut downs, etc.

Results

CAMx modeling results

Figure 2 shows the CAMx-modeled maximum daily 8-h average (MDA8) ozone concentration averaged over three years and the CAMx annual fourth highest MDA8 averaged over three years (ozone design value) for CTRL, CASE1-CTRL, and CASE2-CTRL. Figure 3 shows how the three-year average of the MDA8 will change in each case and over all regions. According to the CAMx results for the CTRL case (Figs. 2a, d and 3), the 2015 NAAQS for ozone is violated in most regions in the USA and the North East, South East, East North Central, Central, and West regions are the regions with ozone design values exceeding 70 ppb in the majority of their areas. By keeping the emissions equal to the 2016 levels in 2050, meaning that no policy- or technology-driven emission reductions happened (CASE1), the average ozone and ozone design value will increase in almost all regions in the USA due to climate change, although slightly (Figs. 2b, e and 3). The largest increase will happen in the South East, South, and Central regions. On the other hand, when emissions are reduced according to the RCP 8.5 scenario (CASE2), considering the effect of both climate change and emission reductions, the ozone concentrations decrease dramatically. This decrease happens more in the North East, South East, and Central regions (Figs. 2c, f and 3). Although the number of days with ozone design values above current standard in the USA increased in CASE1 on average by 5.7 days, with a maximum in the West region (16 days), in CASE2, with emission reductions over the USA, the number of days decreased significantly by 32.5 days (Table 3). A day was considered above 70 ppb for a given region when the maximum 8-h ozone at any grid point within the region was above 70 ppb. As such, Table 3 cannot be compared against actual observations, which are more sparse than the modeled grid cells. A better comparison is through the calculation of the design value at each monitoring site for all the years of interest, as done in the next section.

Projecting 2016 ozone design values to 2050

The air quality modeling results in Fig. 2 came directly from downscaled meteorological fields from a coarse GCM based on RCP 8.5. However, to properly compare the results against ozone monitoring sites, a different method is needed to obtain the future design values, as recommended by EPA (United States Environmental Protection Agency (USEPA) 2016a). Figure 4 shows the ozone design values in CTRL, CASE1, and CASE2 for 480 monitoring stations across the USA which had hourly ozone data during the 2015–2017 summers. In 2016, there were 112 stations exceeding the 70 ppb 2015 NAAQS for ozone, most of which were in the North East, Central, and West regions (Table 4). We applied the relative response factor (RRF) to project the 2016 ozone values from observations to 2050 in both future cases. According to the EPA, the RRF is "the fractional change in 8-h daily maximum ozone between the base and future year." The RRF is based on the average ozone on model-predicted high-ozone days in grid cells in the vicinity of the monitoring site. The modeling guidance recommends calculating RRFs based on the highest 10 modeled ozone days in the base year simulation at each monitoring site. Specifically, the RRF was calculated based on the 10 highest days in the 2016 control case modeling results

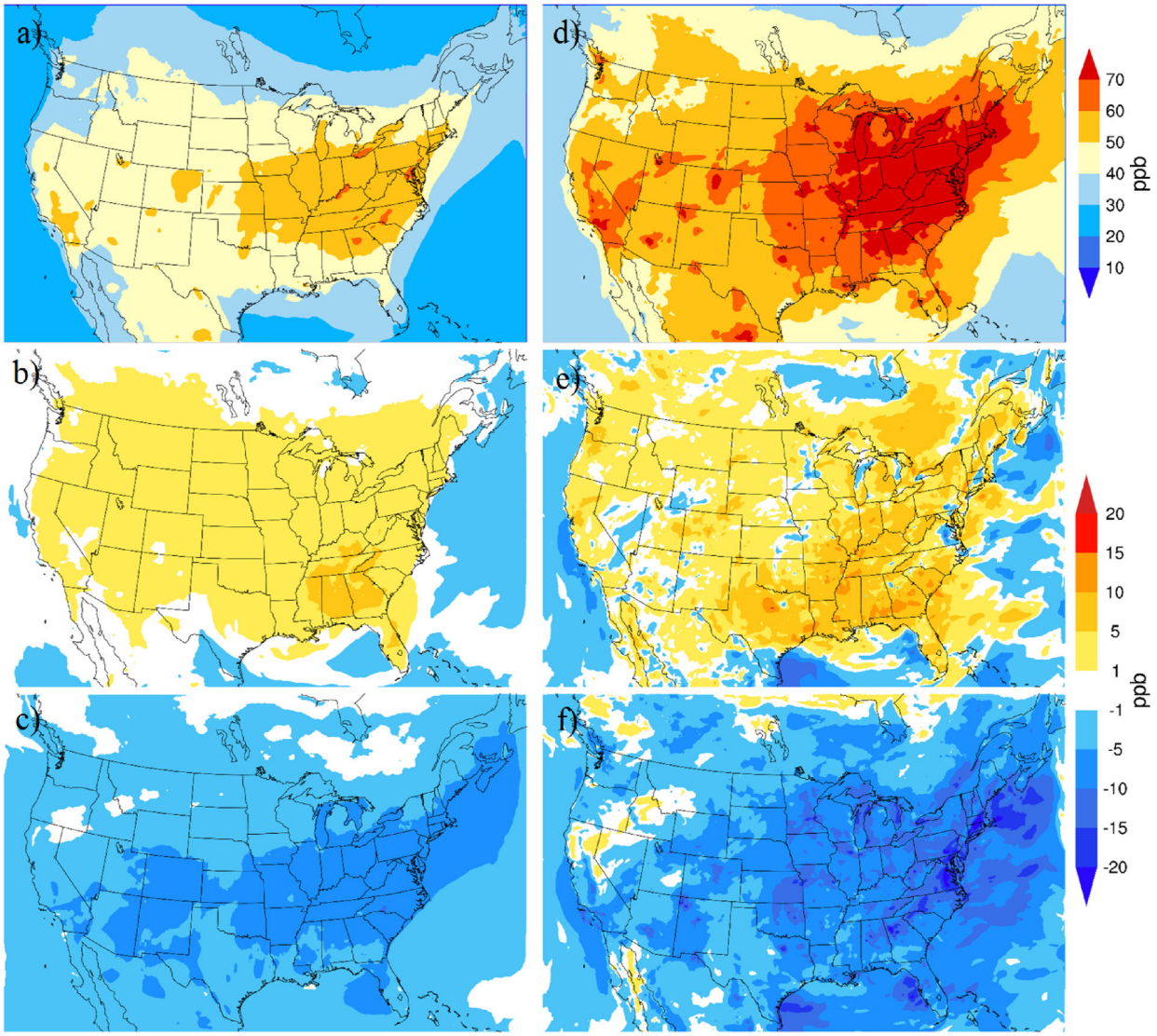

Fig. 2 Year average daily maximum 8-h ozone concentration (**a**) and fourth highest maximum 8-h ozone concentration (**d**) for the CTRL case in ppb; CASE1 - CTRL for year average (**b**) and fourth highest (**e**); and CASE2 - CTRL for year average (**c**) and fourth highest (**f**)

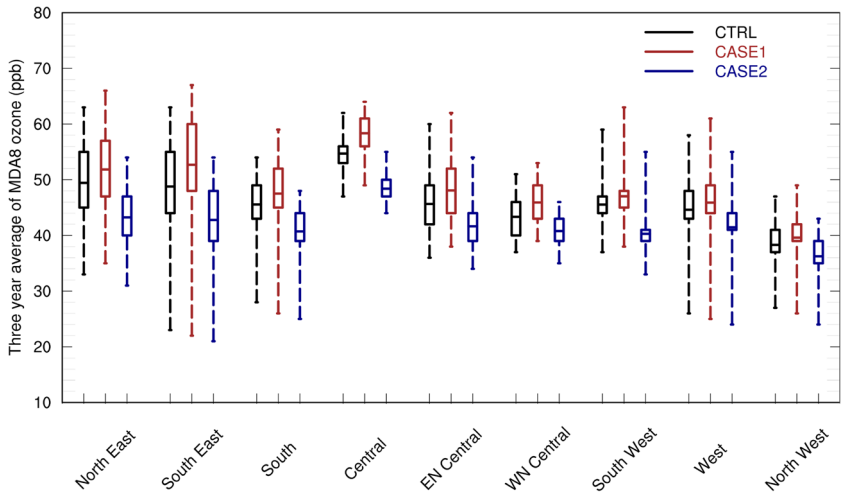

Fig. 3 Three-year average box plot of MDA8 ozone for all nine US regions for CTRL (black), CASE1 (red), and CASE2 (blue)

Table 3 Number of days above 70 ppb and 60 ppb per year in each US climate region

Climate region	N. of days above 70 ppb			N. of days above 60 ppb		
	CTRL	CASE1	CASE2	CTRL	CASE1	CASE2
North East	78	83	28	86	86	66
South East	83	90	18	87	88	66
South	27	39	3	72	79	21
Central	79	80	25	88	88	69
East North Central	55	57	17	76	78	50
West North Central	2	4	0	42	48	1
West	16	32	0	67	69	38
South West	48	53	4	83	86	40
North West	0	1	0	4	9	1

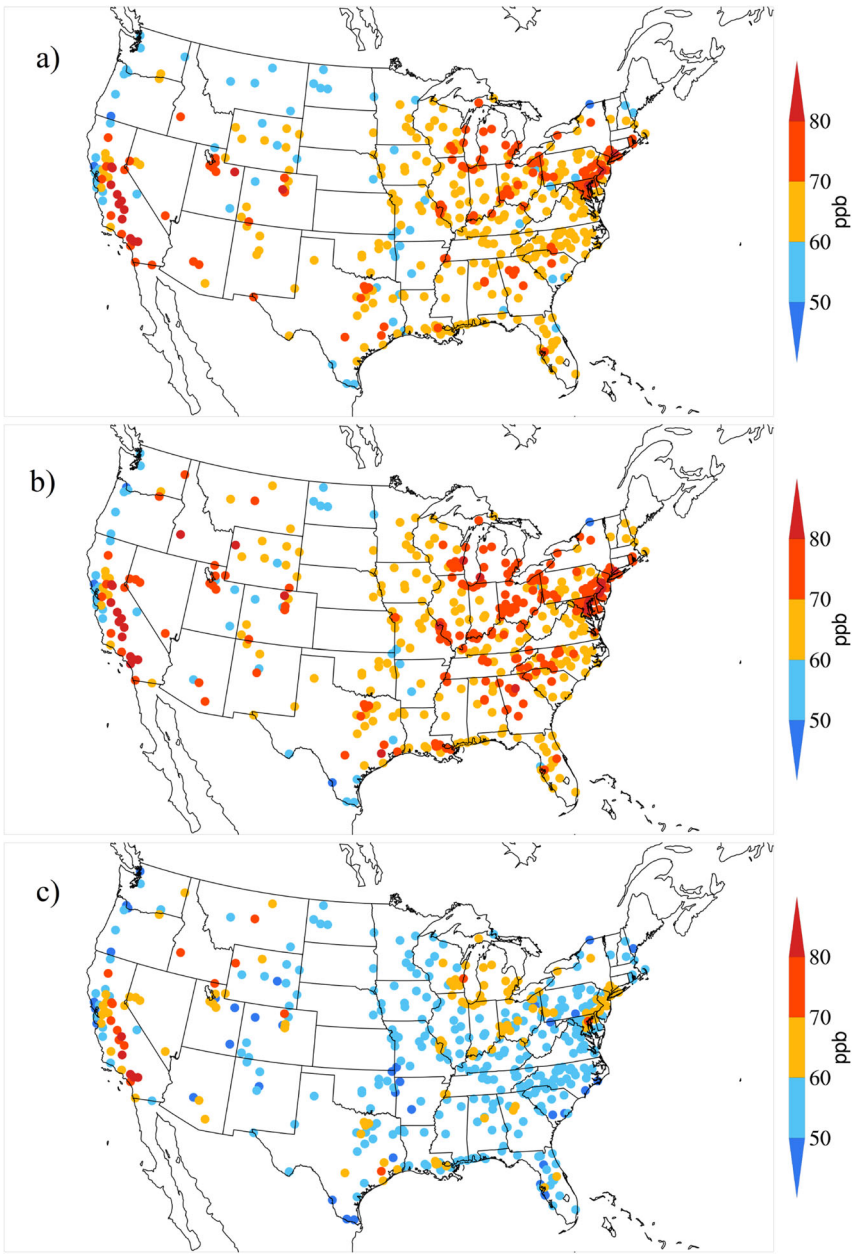

Fig. 4 The 4th highest MDA8 ozone averaged over three years for 480 monitoring stations in the USA. (**a**) CTRL, (**b**) CASE1, (**c**) CASE2

Table 4 Number of stations with the 4th highest MDA8 averaged over three years with ozone above 70 ppb and 60 ppb for 2016, projected 2016 to CASE1, and projected 2016 to CASE2

Climate region	N. of stations above 70 ppb			N. of stations above 60 ppb		
	Obs (2016)	CASE1	CASE2	Obs (2016)	CASE1	CASE2
North East	34	52	1	65	69	31
South East	4	30	0	85	96	5
South	9	16	0	50	57	14
Central	21	59	0	97	103	29
East North Central	12	17	1	36	40	17
West North Central	0	4	2	5	18	5
West	19	23	13	32	32	28
South West	12	12	2	22	18	10
North West	1	3	1	3	4	3
Total	112	216	21	395	437	142

at the grid cells containing the monitor sites. Therefore, by applying the RRF derived from the difference between CASE1 and CTRL cases to the 2016 monitoring stations ozone values, the number of stations above the standard increased from 112 in CTRL to 216 in CASE1 showing that with no emission reductions, due to climate change more stations will exceed current ozone standard. The Central, South East, and North East regions will have the most increase in number of stations exceeding the standard due to climate change by 38, 26, and 18 more exceeding stations respectively (Table 4).

However, the results also show that, with both policy- and technology-driven emission reductions based on RCP 8.5, there would be 21 stations in the USA with ozone values exceeding the 70-ppb standard and most of the stations would be located in the West region. This means that, even with the less stringent emission reduction scenario of RCP 8.5 than any other RCPs for ozone precursors, the South East, South, and Central regions, which had 4, 9, and 21 stations above standard, respectively, will have no stations above ozone standards. However, still 13 stations in the West region will exceed the standard. Although the results show that in future by reducing emissions according to RCP 8.5 the number of stations exceeding the 2015 ozone standard will drop significantly, we note two important caveats.

First, we held the biogenic emissions constant in both future cases, but there is a probability of an increase in the future ozone levels due to the increased biogenic emissions that higher temperatures will cause. As such, in future, we might have more stations exceeding the current standard than the abovementioned 21.

In addition, as ozone is a continuous variable, in 2050, there will still be significant ozone pollution close to the 60-ppb threshold. This number could be important when for example, a more stringent national ozone standard be defined by EPA at that time. So, the regions will have difficulties attaining a more stringent ozone standard in 2050. Table 4 shows that, with a 60-ppb ozone standard, there would be 395 out of 480 stations above the new standard in 2016. There would be no significant change in the future case with 2016 emissions in the number of stations above the possible future standard, but in the future case with 2050 emissions with huge emission reductions for ozone precursors (more than 40% reduction of 2016 values), 142 stations will have ozone levels above the 60-ppb standard. In this case, the North East, Central, and West regions will have the most stations exceeding the future ozone standard.

Links between meteorology and ozone concentrations

It is well known that there is a strong positive correlation between ambient temperature and ozone concentrations and a negative correlation between relative humidity, precipitation, and ozone (Fu et al. 2015; Jacob and Winner 2009; Fu et al. 2015; Camalier et al. 2007). Here we compare average 2-m temperature (T2), average cumulative precipitation (PRECIP), and average relative humidity (RH) between current and future climate over the USA. As shown in Fig. 5, in future climate, the average T2 in almost all regions in the USA is expected to be higher. This increase is more intense in the North East, South East, Central, and South regions. However, a slight decrease is expected for parts of the South West and South regions. In average, the temperature will increase by 1.1 °C over the USA. Precipitation will decrease for most parts of the USA, including all the eastern and central regions, and will increase in parts of the western regions. Precipitation and relative humidity show a similar pattern in most regions in the USA. The largest reduction in precipitation will happen in the South East, Central, and North East regions by -52.4%, -48.3%, and -46.1% on average (Table 5). Relative

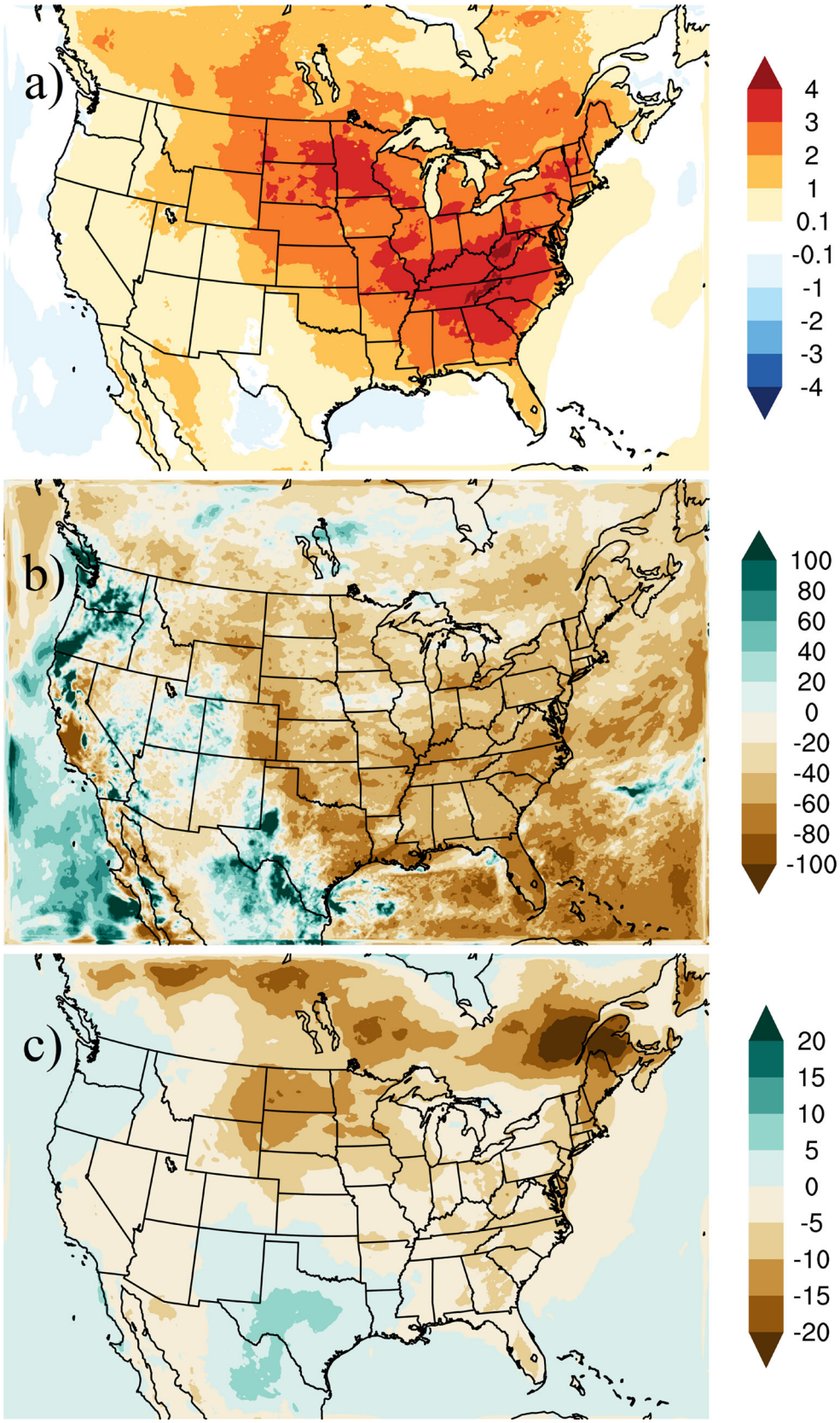

Fig. 5 Projected relative changes of (**a**) 2-m temperature (K), (**b**) accumulated precipitation (%), and (**c**) relative humidity (%) from 2015–2017 to 2049–2051 under RCP 8.5

Table 5 Average changes in meteorological variables (T2, RH, and PRECIP) and average ozone change for CASE1-CTRL and CASE2-CTRL

	ΔT2 (°C)	ΔRH (%)	ΔPRECIP (%)	ΔMDA8 (ppb) CASE1-CTRL	ΔMDA8 (ppb)
North East	2.3	−6.9	−46.1	2.1	−6.3
South East	2.2	−3.7	−52.4	3.8	−6
South	0.9	2.2	−24.3	2	−4.9
Central	3.1	−4.1	−48.3	3.6	−6.3
East North Central	2.5	−6.2	−35.8	2.5	−2.6
West North Central	2	−5.9	−31.8	2.4	−4.1
West	0.5	−0.9	1.2	1.2	−5.2
South West	0.8	−0.7	−10.5	1.4	−3.1
North West	0.6	0.5	20.7	1.3	−2.1

humidity will also decrease in all regions except the North West and South by -3% in average and up to -6.9% in the North East region.

The relationship between average average MDA8O3 and T2 was investigated for the current and future climate conditions. We found that, during the summer, MDA8 ozone increases by 0.9 ppb per one degree increase of temperature in the current climate conditions. However, in the future climate, this sensitivity will increase to 1.2 ppb per one degree temperature increase, showing that the sensitivity of ozone to temperature will be higher in the mid-century climate (CASE1) than current climate (Fig. 6 and Table 6). The increase is highest in the South East region. Although there are a variety of factors related to the non-linear O3 formation, this increase can be related to the high temperatures in that region. While the summer temperatures in this region are high, an increase in the temperature can lead to a higher O3 (Table 6).

The effect of temperature on ozone levels in the Northeastern United States is highest and the negative correlation of RH with ozone levels is highest in the Southeastern United States (Jacob and Winner 2009). As shown in Fig. 5, the average T2 and RH over the Southeastern United States will increase and decrease, respectively, due to climate change, which cause elevated ozone concentrations in this area up to 3.8 ppb (Fig. 2a). Another reason for this dramatic increase over the South East region is that any increase in relatively higher temperatures in this region will favor ozone formation. The relatively lower ozone increase in the South region is due to the concomitant increase in RH and PRECIP, although the T2 is going to increase in this region too. In the Western United States (South West, West, and North West regions), where temperature, relative humidity, and precipitation changes are smaller, the increase in average MDA8 ozone is relatively lower than other regions.

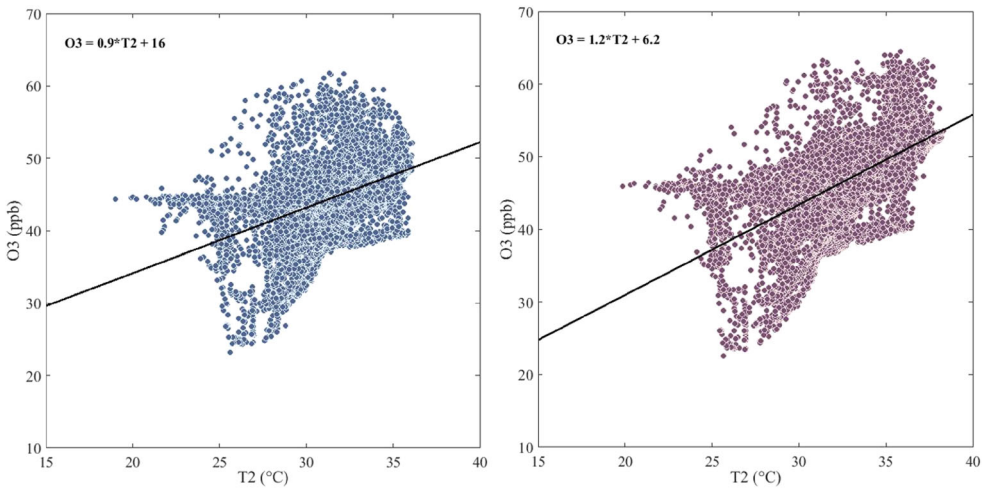

Fig. 6 The three-year average MDA8 ozone and 2-m temperature sensitivity over the USA for (**a**) CTRL and (**b**) CASE1

Table 6 Temperature and ozone sensitivity

Climate region	ΔT2 (°C)	ΔO3 (ppb) (average)	ΔO3 (ppb) (4th highest)
North East	1.74	2.1	3.3
South East	0.76	3.8	3.9
South	0.29	2	2.7
Central	1.13	3.6	3.7
East North Central	1.22	2.4	3.4
West North Central	1.64	2.5	6.8
West	0.91	1.4	1.3
South West	0.80	1.2	−0.7
North West	0.77	1.3	4

Conclusions

In this study, we used regional and global air quality (CAMx, GEOS-Chem) and climate models (WRF, CESM) to compare future ozone levels under two different scenarios with current ozone in the USA. The first assumes no change in emissions (neither policy- nor technology-driven); thus, the effect of only climate change on ozone is considered. The second assumes that emissions will change in the USA following the RCP 8.5 scenario (both policy- and technology-driven) until 2050.

CAMx results showed that, if climate change alone is considered, average MDA8 in all regions in the USA will increase (Fig. 3), with the highest increase over the South East and Central regions by 3.8 ppb and 3.6 ppb respectively. Although the average 2016 design value for the South East region was 64.3 ppb and with this increase the region on average will not violate the ozone standard, there are many areas in this region (Fig. 4) that are currently above or close to the 2015 ozone standard and for which this increase will cause problems in attaining the current ozone standard. As shown in Table 4, the 3.8 ppb and 3.6 ppb increase in the South East and Central regions will cause 26 and 38 more stations to violate the current ozone standard.

On the other hand, if not only climate change but also decreasing emissions over the USA under RCP 8.5 scenario are considered, many regions will actually be in attainment of the current ozone standard (Table 4). The West region will still have 13 stations violating the standard, indicative of the high ozone levels in that region. Although RCP 8.5 projects the lowest emission reductions among all RCPs, it seems to be enough for certain regions (e.g., South East, South, Central). But if a stricter ozone standard will be introduced between now and 2050 (e.g., 60 ppb), which is already being discussed, still 142 stations will violate that standard over the whole USA. Also, the biogenic and boundary conditions are held constant during the CASE1 and CASE2 simulations, which could potentially increase the expected ozone levels.

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